Views

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Cold atom interferometry for inertial sensing in the field

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Abstract: Atom interferometry is one of the most promising technologies for high precision measurements. It has the potential to revolutionise many different sectors, such as navigation and positioning, resource exploration, geophysical studies, and fundamental physics. After decades of research in the field of cold atoms, the technology has reached a stage where commercialisation of cold atom interferometers has become possible. This article describes recent developments, challenges, and prospects for quantum sensors for inertial sensing based on cold atom interferometry techniques.

Keywords: atom interferometry; cold atoms; gravimetry; inertial sensing; navigation; quantum sensors.

Matter-wave interferometry is one of the most advanced measurement techniques known today. It utilises the dual nature of matter, first proposed by Louis de Broglie almost one century ago, in which particles can exhibit wave behaviour. Experimentally, matter-wave interferometry was first demonstrated in 1953 using electrons [1] and in 1974, using neutrons [2]. With the advent of laser cooling [3] and other cooling techniques, Bose–Einstein condensation was achieved in 1995, where millions of atoms collectively form a macroscopic matter wave [4, 5]. More recently, much larger molecules have also been shown to exhibit wave properties, such as biological molecules and fluorophores [6]. Interferometry using antimatter has also been reported last year [7].

Optical interferometers using laser light are today used in a broad range of applications from fundamental research [8] to diagnostic tools [9] and navigational aids [10]. Because atoms have mass, atom interferometers are many orders of magnitude more sensitive to external forces than optical interferometers of comparable arm length. This has stimulated enormous interest in utilising atoms for precision measurements. Thanks to advances in laser cooling and trapping, as well as precision control, ensembles of atoms are now routinely prepared at microkelvin temperatures. At these temperatures, both the internal states and motional states of the atoms can be precisely controlled using microwave and optical manipulation techniques. This makes cold atoms prime candidates for matter-wave interferometry, and they are already being used to push the limits of interferometer sensitivity.

The applications of cold atom interferometry (CAI) are many. In terms of fundamental physics, precise measurements of fundamental constants have been made, such as the fine structure constant [11] and the gravitational constant [12, 13], along with tests of general relativity [14] and the weak equivalence principle [15]. CAI also has a wealth of potential for sensing in applications such as gravimetry, magnetometry, accelerometry, and rotational sensing.

One of the more widely used CAI techniques utilises laser-cooled alkali atoms as the matter-wave source and Raman pulses in the place of the physical glass beam splitters used in optical interferometers. The first demonstration of this type of interferometry was reported in 1991 using sodium atoms [16], and many more have followed. A general schematic of the measurement principle is shown in Figure 1. To begin with, a magneto-optical trap is formed inside a vacuum chamber. The atoms are then prepared in an internal state that is insensitive to magnetic fields, which add unwanted phase shifts. Using Raman light pulses, this atomic sample is coherently split into a quantum superposition of two components, which have different internal and momentum states, and then recombined after an evolution time. During this evolution time, the atoms in the two interferometer "arms" acquire a phase difference due to the presence of external fields and inertial forces. This phase difference is then read out by measuring how many atoms are in a particular state at the end of the sequence.

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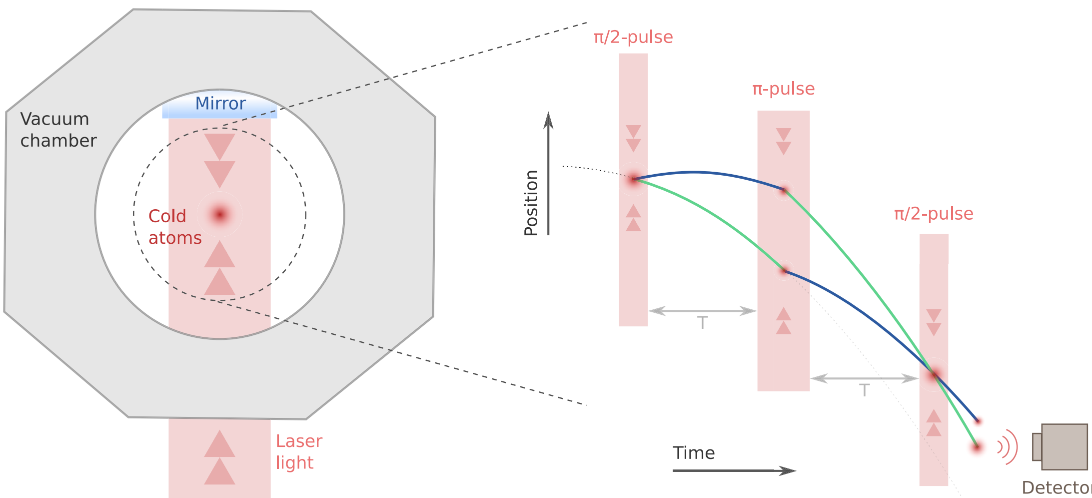

Figure 1: Atoms are trapped and cooled inside a vacuum chamber (left). A pair of Raman beams act on the atoms in the vertical direction in a three-pulse sequence (right). The $\pi/2$ pulses act as beam splitters, while the π pulse acts as a mirror. As the atom cloud falls, the first pulse splits the cloud into two internal energy states and imparts momentum onto one of them (blue trajectory). The second pulse flips the momentum states and internal states, and the final pulse recombines the two clouds. If the clouds accumulated different phases along their respective paths, the final populations in the two internal states will be different.

By applying light pulses in various configurations and directions, different types of measurements can be made.

The high sensitivity of atom interferometers is a double-edged sword; since atom interferometers are capable of very precise measurements of inertial forces, they are also sensitive to the Coriolis effect and tidal variations. In addition, phase shift contributions can come from wavefront aberrations in the Raman beams and Guoy phase, the second order Zeeman effect, magnetic field gradients, two-photon light shifts, and other effects. Such effects must be accounted for in order to perform accurate absolute gravity measurements, as was recently done for a mobile CAI survey by Wu et al. [17].

Despite immense gains in sensitivity using CAI, there are many challenges in converting table-top lab-based systems into high-performance instruments for real-world applications. Besides minimising size, weight and power consumption, stability against vibration noise is a major obstacle to overcome. Laboratory demonstrations of CAI typically utilise active vibration isolation stages that work only for small vibration amplitudes and are not suitable for mobile applications. Additionally, robust narrow linewidth lasers required for the cooling and manipulation of atoms are not widely available in the near-infrared range, in comparison to what is readily available at telecom wavelengths. Despite these difficulties, CAI has been demonstrated in several highly challenging environments, such as aircrafts [18, 19] and on a ship [20], by making use of auxiliary classical accelerometers. Preliminary experiments have also been performed on a sounding rocket [21]. However, vibration noise remains one of the major factors that limit sensitivity in such mobile interferometers in comparison to their stationary counterparts.

In addition to research efforts, commercial CAI-based gravimeters are already on the market [22] and are used in applications such as metrology, earthquake research, and monitoring of volcanic activity. These gravimeters are transportable but can only operate under static conditions. A commercial mobile gravimeter that can acquire data while in motion is yet to be on the market. Such a device opens up major opportunities in surveying for underground resources, such as oil and gas reserves, minerals, aquifers, and metal deposits. Additionally, detection of human-made underground structures such as boreholes, mineshafts, and tunnels is also feasible. In particular, detection of underground features in urban environments can prevent delays and unforeseen costs in civil underground infrastructure projects, such as digging tunnels for light rail passenger transport.

Extending one-dimensional CAI to three dimensions enables measurements of acceleration and rotation along all three axes. Together, these can form an inertial measurement unit (IMU), which can be used for inertial navigation systems (INSs). Navigation technologies generally rely on the Global Positioning System (GPS) or a combination of classical IMUs and GPS due to performance limitations of IMUs alone. Because GPS is vulnerable to spoofing and jamming, there is a need to develop completely independent navigation systems for high security applications. Additionally, there are situations where GPS is not available, such as underwater and underground. CAI-based IMUs have the potential to enable navigation independent of GPS due to their high sensitivity and long-term stability. Laboratory demonstrations of CAI gyroscopes have already matched the performance of state-of-the-art optical gyroscopes in terms of sensitivity and long-term stability [23], though with limited dynamic range. However, by integrating CAI-based INSs with conventional INSs, this problem can be overcome [24]. With the advent of autonomous road vehicles, air planes, and ships, there is even more scope for GPS-independent inertial navigation. These types of applications require miniaturised systems and low cost, which is a major challenge for CAI. However, there is considerable effort being made in this direction, such as development of atom chip-based systems [25].

A mobile single-axis gravimeter can provide two-dimensional contour data of a region. If we extend a CAI setup to multiple axes [26] using multiple clouds, a full tensor gravity gradiometer (FTGG) can be realised [27]. By measuring gravity gradients along each direction, a three-dimensional picture of the gravity landscape can be inferred, allowing us to build up an image of the Earth's subsurface. Such measurement capability is highly applicable to geophysical exploration of natural resources, such as hydrocarbons and mineral deposits, allowing for noninvasive estimation of both quantity and depth of a particular resource [28]. Classical FTGG systems built by Lockheed-Martin have been used for airborne surveys of a mineral mining site, with results in agreement with ground-based measurements [29].

The concept of cold atom FTGG measurements is illustrated in Figure 2. Starting with a single atomic cloud cooled to a few microkelvin, CAI along three orthogonal axes is performed, which spatially separates and recombines atomic ensembles along each direction. Through these measurements, we can construct a gravity gradient tensor:

$$\Gamma = \begin{bmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{bmatrix}.$$

where $T_{ij} = \frac{\partial^2 g}{\partial i \partial j}$ and g is the gravitational potential. This tensor, Γ, is symmetric and traceless, meaning that $T_{ij} = T_{ji}$ and $T_{xx} + T_{yy} + T_{zz} = 0$. Therefore, only five of the nine components are independent, and the entire tensor can be determined from those five components. Both diagonal and off-diagonal components can be measured using CAI-based absolute accelerometers operated in a differential mode [30]. A single shot measurement protocol of three rotation and acceleration components has also been proposed [26], making the development a compact CAI-based FTGG instrument feasible [27].

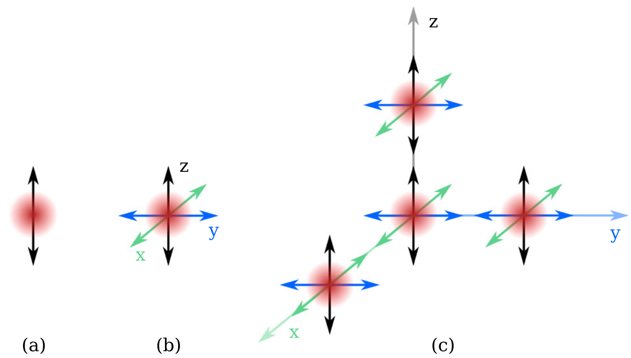

Figure 2: Different configurations of interferometry. (a) A single cloud, single-axis measurement (gravimetry). (b) A single cloud, multiaxis measurement (IMU). (c) A multicloud, multiaxis measurement (FTGG). FTGG, full tensor gravity gradiometer; IMU, inertial measurement unit.

FTGG is also useful as a navigation tool. Once gravity in three dimensions is fully mapped out over a particular region, the FTGG tensor becomes a unique fingerprint for any position [31]. However, gravitational forces are not static; due to time-varying factors, such as tides, atmospheric changes, tectonic shifts, and construction projects, there are substantial effects on local gravity. These effects can be accounted for by a combination of mathematical models and fixed base stations making continuous measurements [32]. Navigation using map matching can provide a completely passive navigation and positioning system based on the gravity pattern [31].

CAI-based inertial sensors have the potential to drive a major paradigm shift in many sectors. Gravimetry and gradiometry can support not only geophysics research but also commercial ventures such as resource exploration and civil engineering. Presently, the ocean floor remains largely unexplored, as currently available seismic sensors are difficult to operate underwater or underneath ice caps. Furthermore, in areas where seismic surveys have been completed and potential resource features have been identified, local gravity surveys can reduce further exploration costs drastically by overlaying high-resolution gravity data over coarsely spaced seismic data. Advancements in inertial navigation can supplement or replace GPS-based navigation for vehicles operating autonomously, particularly underwater and underground.

Development of CAI-based sensors is happening rapidly on many fronts, not only in measurement techniques but also in electronics, miniaturisation of core components, and software. Early stage CAI-based quantum sensors are already available on the market today, and more sophisticated and versatile systems will arrive in the near future. Atomionics is building the next generation of CAI-based inertial sensors, with the roadmap leading to mobile FTGG devices. These cutting-edge instruments will transform both navigation and resource exploration, as well as numerous civil engineering and scientific applications.

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